Nanoenergetics, Nanomaterials, Nanodevices, Nanocomputing –Putting the pieces together

European Materials Research Society

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Intel Corp

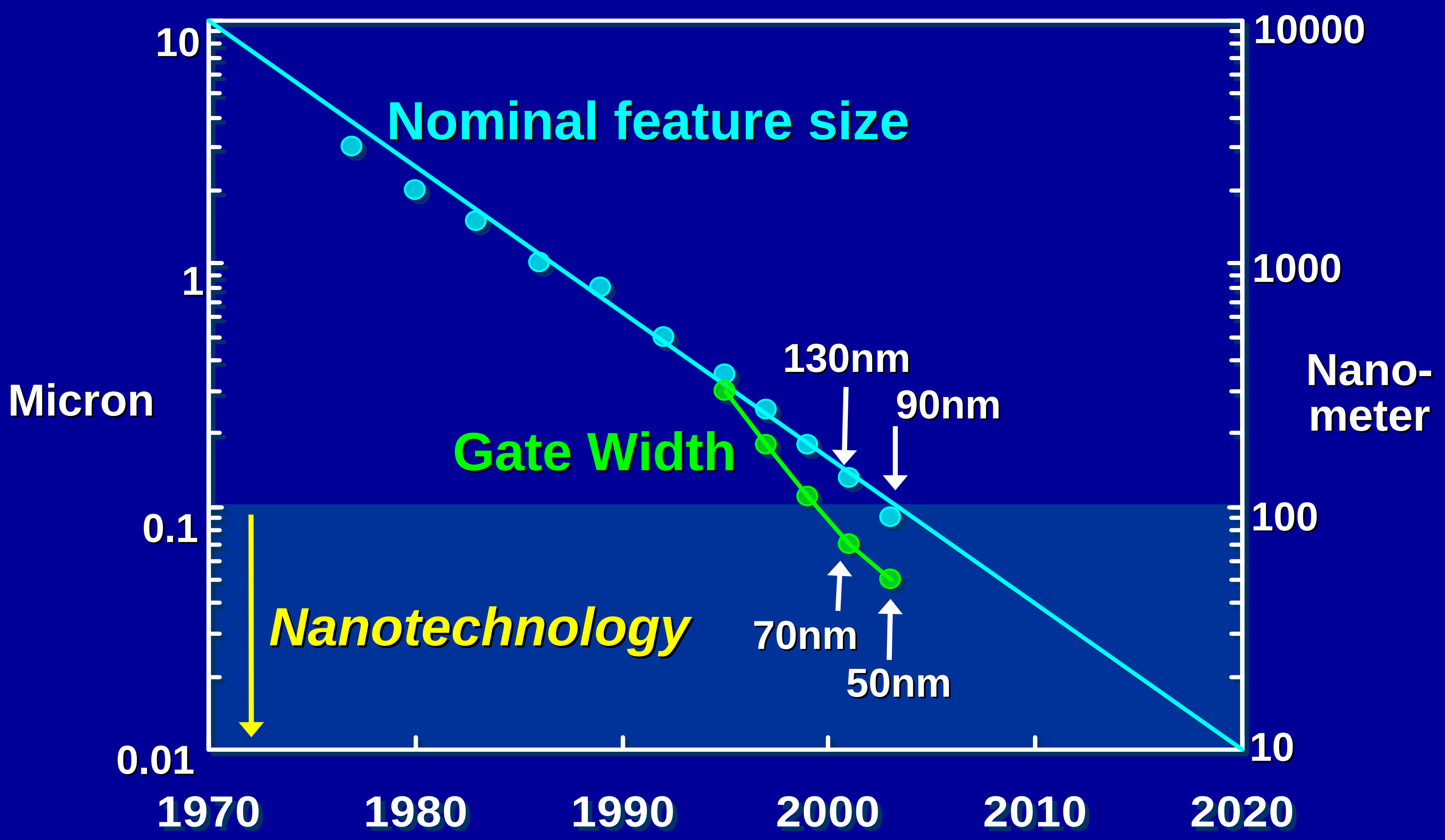
Key messages

- CMOS will be the logic technology of choice for the indefinite future(15-16 yrs)
- Research to develop robust, new information processing technologies is needed now.
- Relevant scientific pieces exist – *it's time to start putting the pieces together*

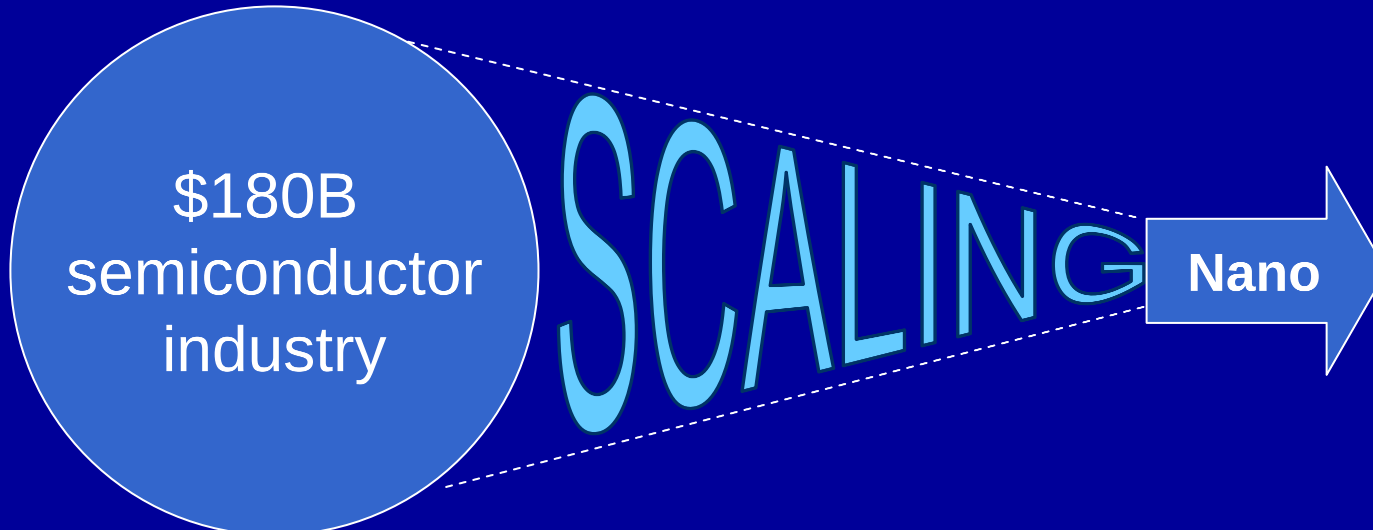
Agenda

- CMOS, scaling and Moore’s Law
- Defining the limits of CMOS
- What are the options?
- Exceeding the limits
- Conclusions

Silicon Nanotechnology is Here!



Extension of Moore's Law

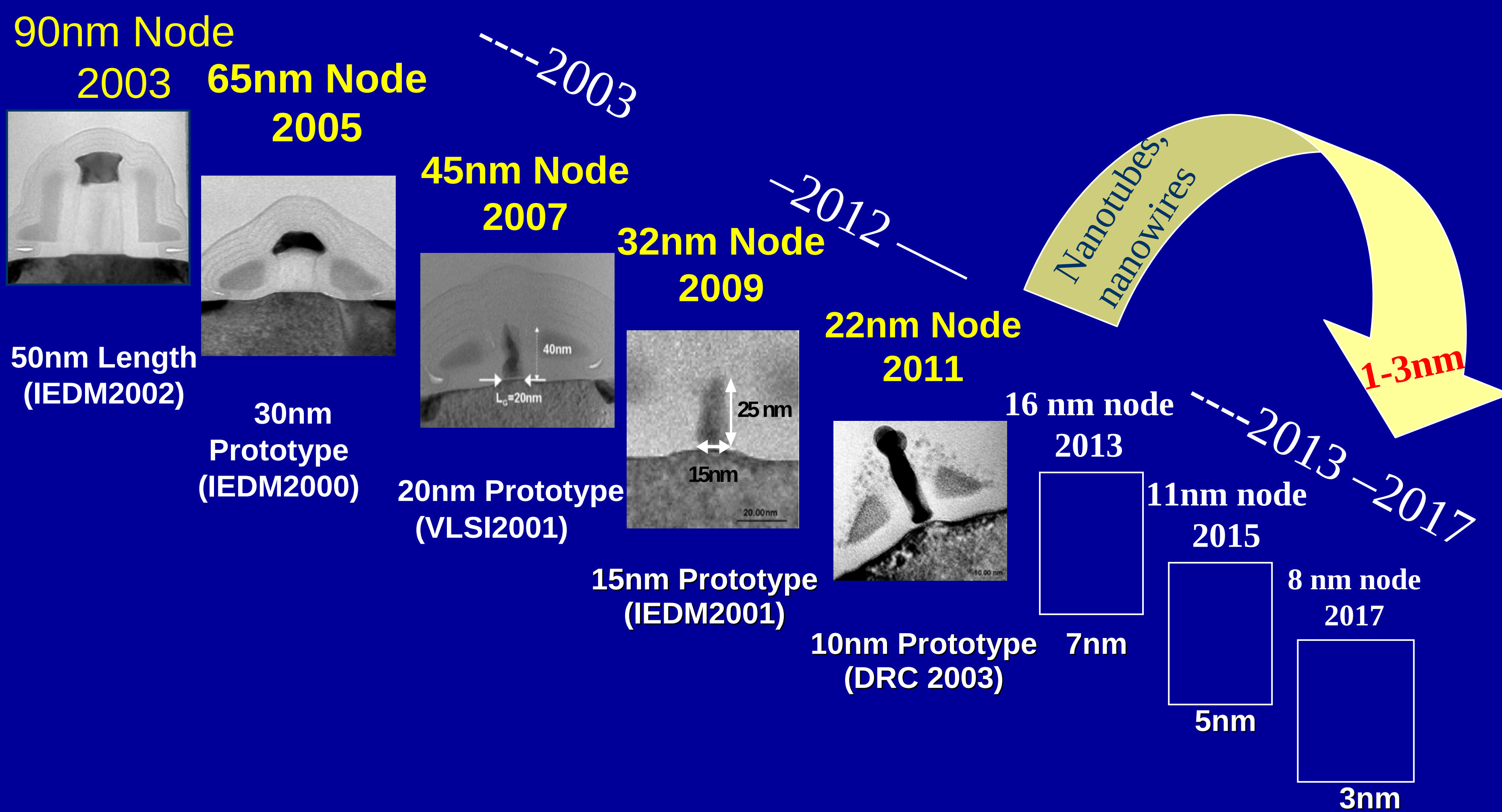


1. Scaling device dimensions downward
2. Scaling wafer diameter upward

	1990	1995	2000
DRAMs	4 MB	64 MB	1 GB
Feature size	0.8 µm	0.35 µm	0.15 µm
Wafer diameter	6"	8"	12"
Cost per Megabit	$6.50	$3.14	$0.10

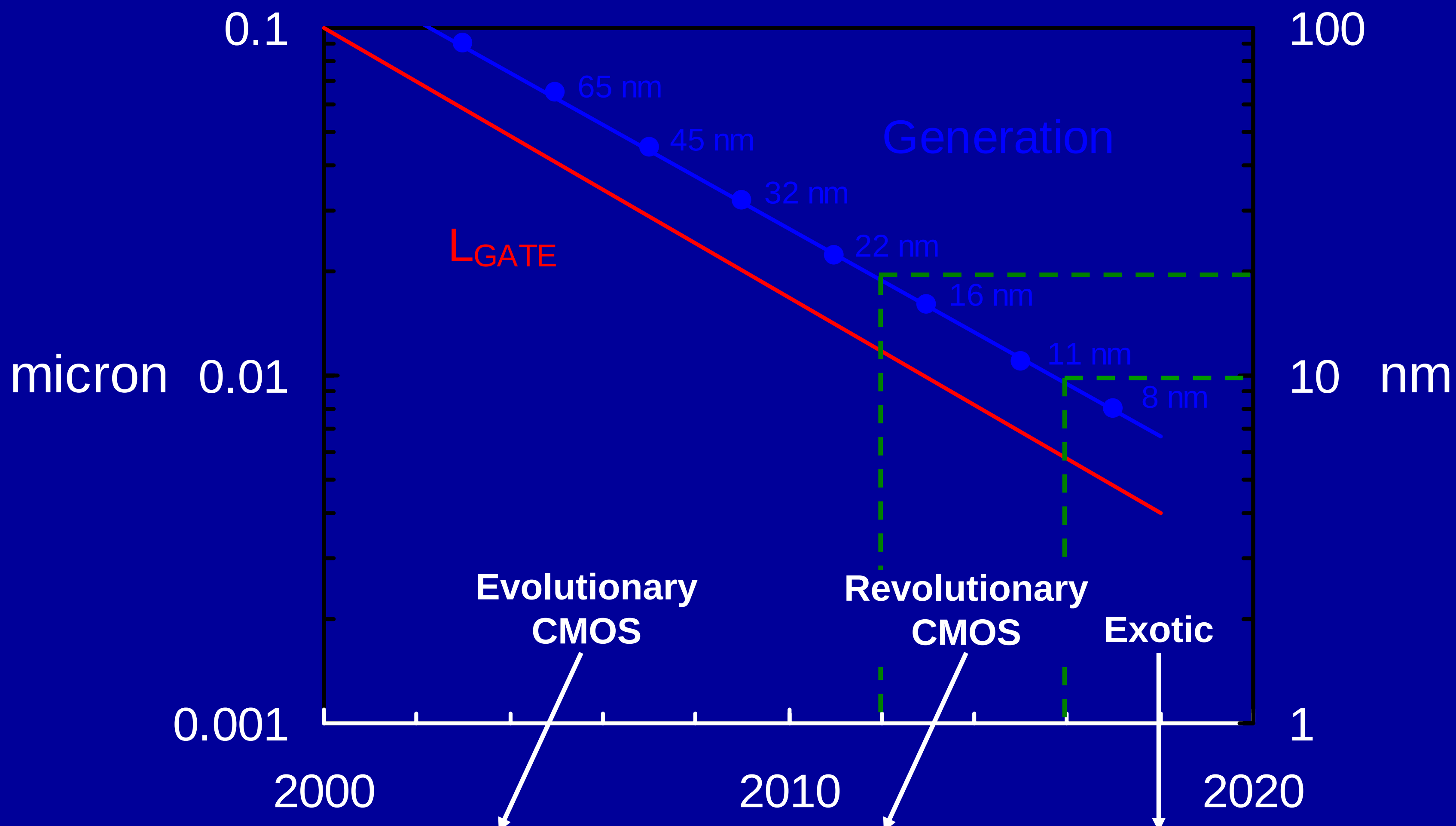
Powerful economic engine will drive innovation

Nanotechnology will extend CMOS scaling



Innovations like quantum dots,
Nanowires, Naotubes, etc.

Nanotechnology Eras-Cd <100nm



Classical physics

Classical physics-quantum corrections

Intrinsically quantum mechanical

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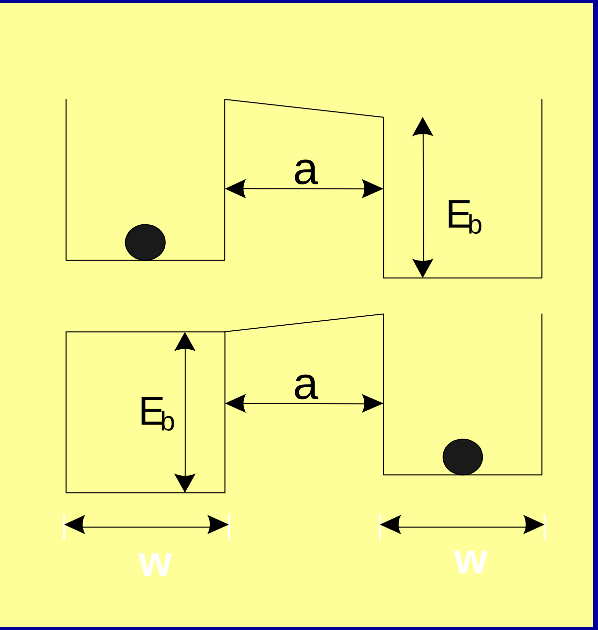
Theoretical Limits to Scaling

- If we assume a simplified model of a switch that can describe an arbitrary nanoelectronic device
  - A dual quantum well separated by an energy barrier operating at room temperature
- And apply basic quantum mechanics
  - Heisenberg uncertainty principle
  - Energy levels in a quantum well
  - Quantum mechanical tunneling probability
- Room temperature limit:
  - Characteristic dimension ~ 1.5 nm
  - Switching energy = 0.017 ev
  - Switching speed ~ 0.04 ps



See V. Zhirnov, et. al., Proceedings IEEE, Nov. 2003

Theoretical, asymptotic results

- Minimum device size ~ 1.5 nm
- Energy per transition~0.017ev =$2.7X10^{-21}$J
- Switching time ~0.04 ps

$$P = \frac{n_{\max} E_{bit}}{t_{\min}} = 3.7 \times 10^{6}\ \mathrm{W/cm^2}$$

For densely packed, 100% duty cycle devices

More realistic results

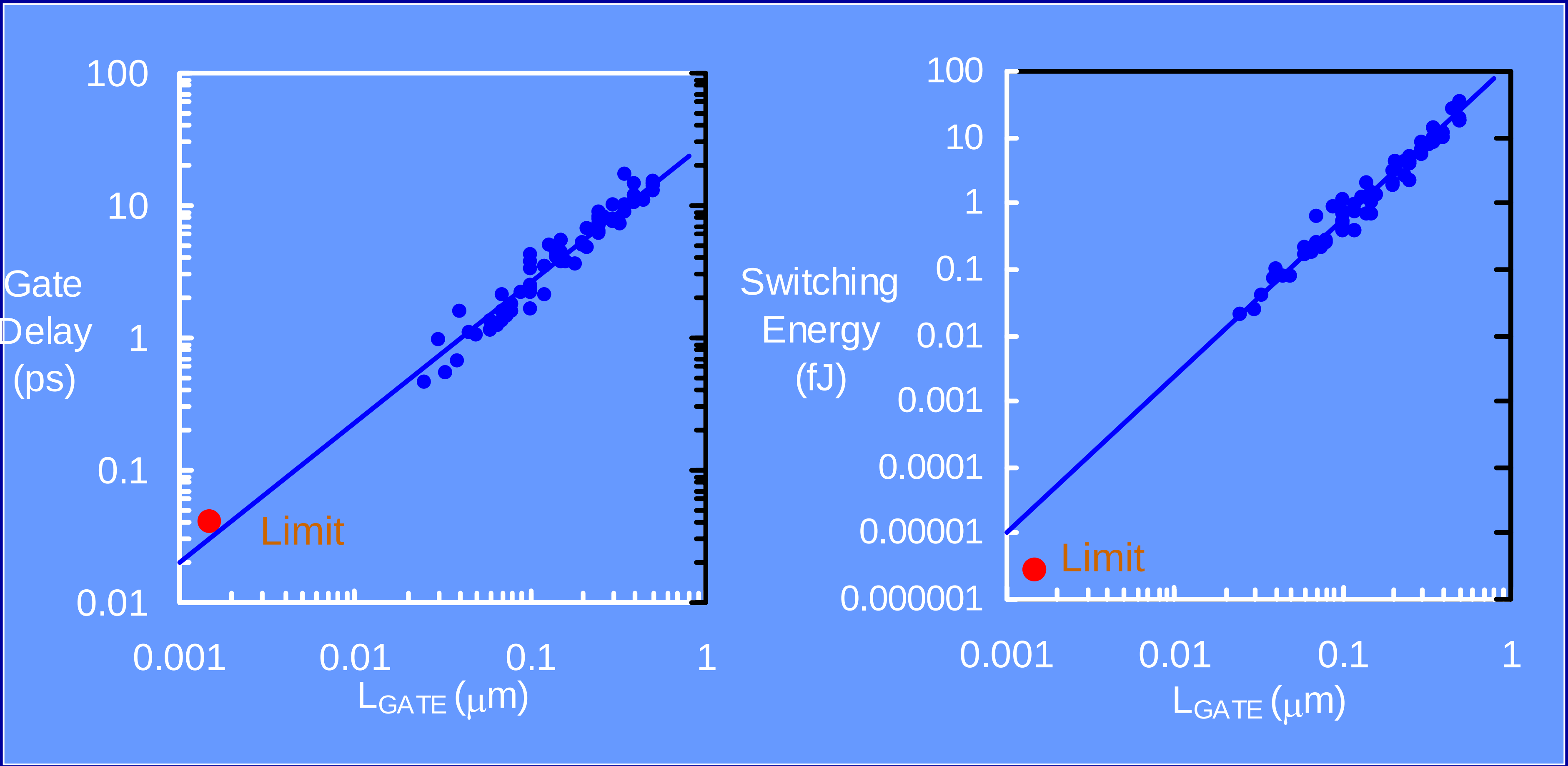
$$P = \frac{n_{\max} E_{bit}}{t_{\min}} = 3.7 \times 10^2 \text{ W/cm}^2$$

With duty cycle~1 %

Active transistors~1 %

Total power density = 370 W/cm^2

Where are we now?



Current CMOS device scaling close to ideal

A long way to go to theoretical limit

What does this say?

- Even if it is possible to build a very fast and small *electronic* switchs based on nanodots, nanotubes, nanowires, molecules, …., the thermal dissipation limit will force them to be slowed down and spread out.
- We can perhaps build *electronic* devices smaller than CMOS but we won’t operate them faster and they won’t be cheaper (no density scaling) than CMOS

What does this analysis mean?

- It shows eventually thermal effects will limit scaling (~2020)
- It shows that no charge based device can beat scaled CMOS
- It shows that eventually alternative logic devices will be required
  - We need to initiate and continue research into alternative logic technologies

Many strategies exist for extending scaling until 2020!

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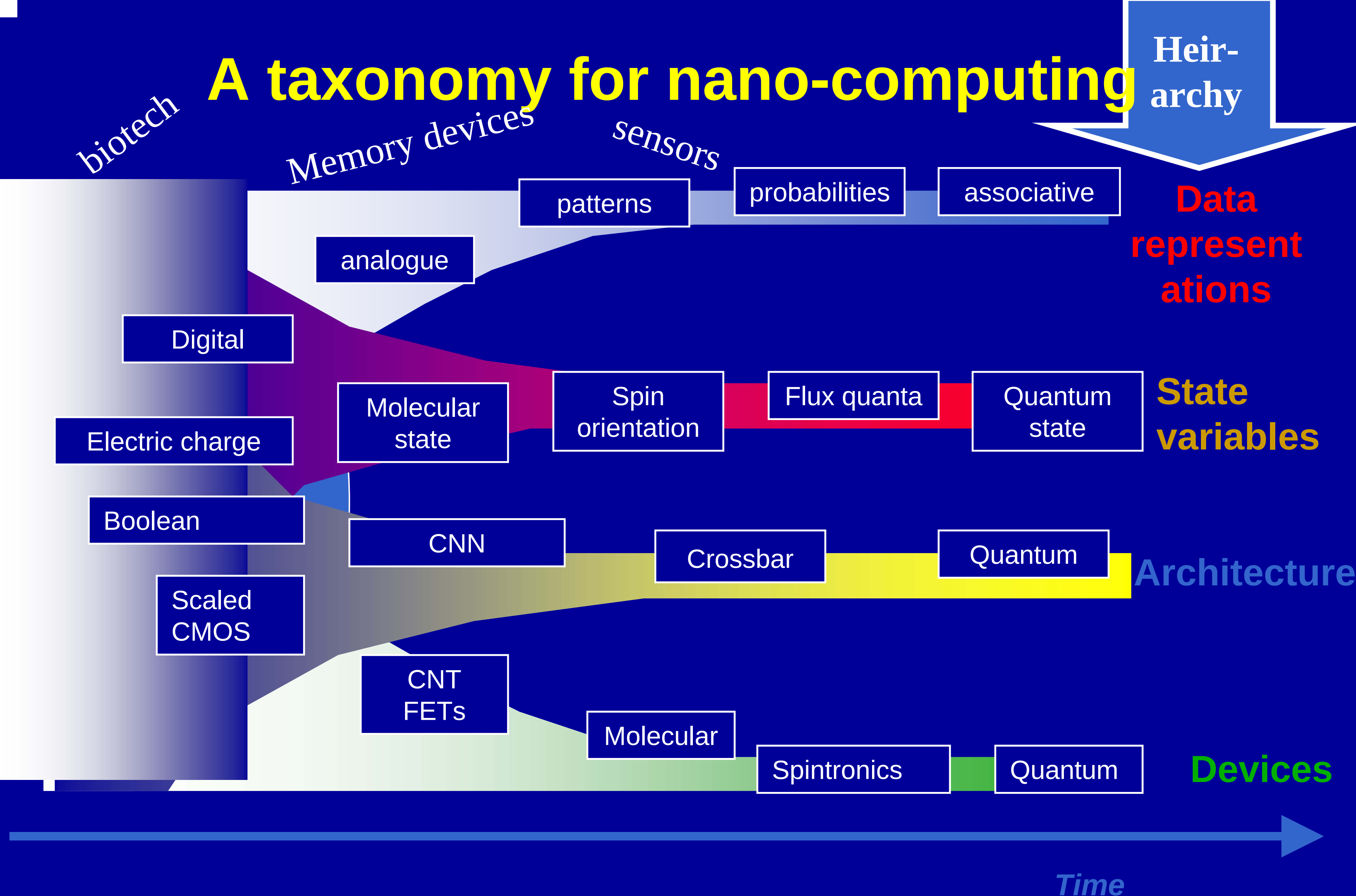
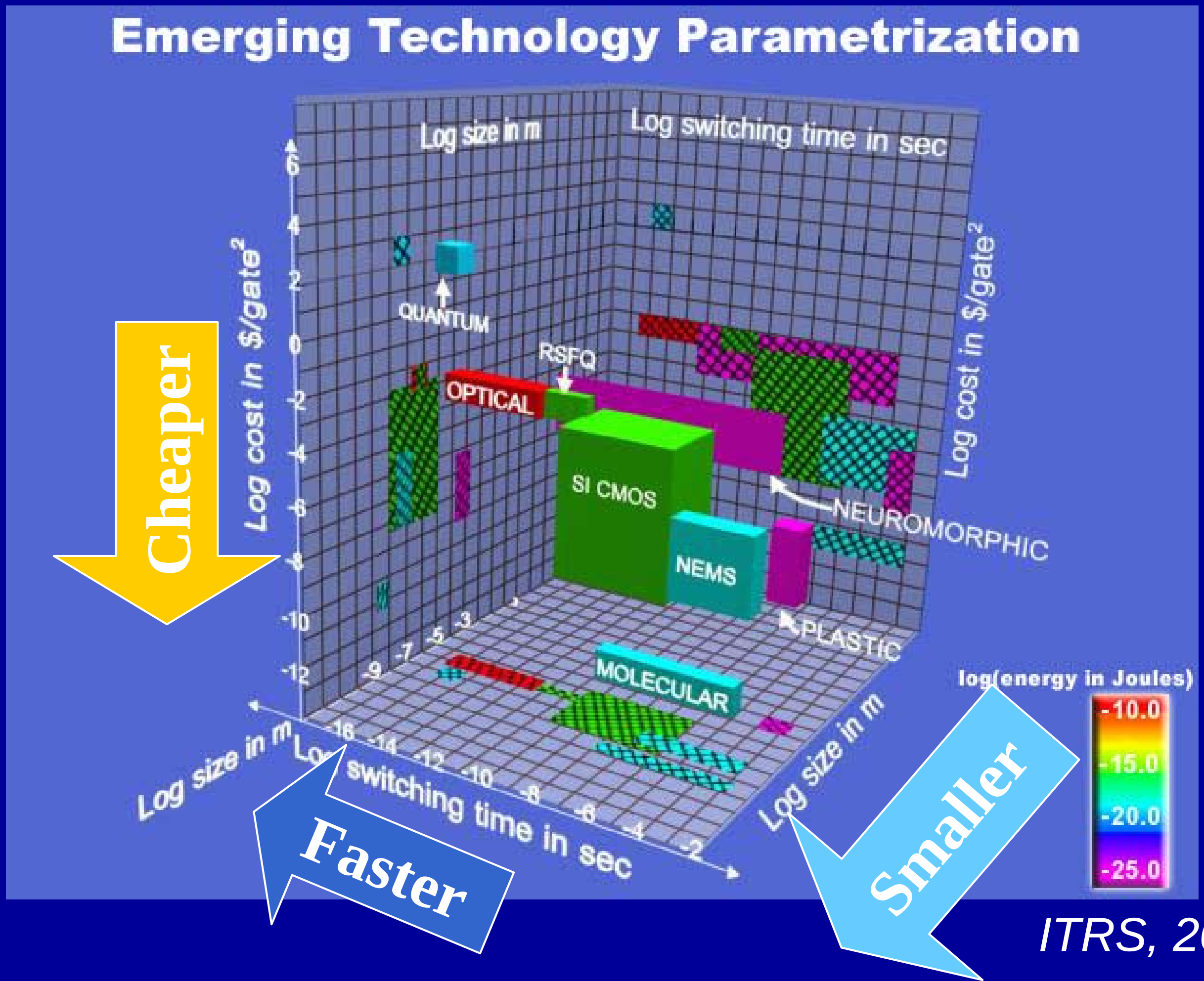
A taxonomy for nano-computing



Nanocomputing involves more than nanodevices

Some alternative logic devices



ITRS, 2001

Nothing beats scaled silicon but other things can compliment

Technology Performance and Risk Evaluation Emerging Research Logic Devices –ITRS 2003

Potential/Risk

Logic Device Technologies	*Performance [A]*	*Architecture compatible [B]**	*Stability and reliability [C]*	*CMOS compatible [D]***	*Operate temp [E]****	*Energy efficiency [F]*	*Sensitivity Δ(parameter) [G]*	*Scalability [H]*
1D Structures	**2.3/2.2**	**2.2/2.9**	**1.9/1.2**	**2.3/2.4**	**2.9/2.9**	**2.6/2.1**	**2.6/2.1**	**2.3/1.6**
RSFQ Devices	**2.7/3.0**	**1.9/2.7**	**2.2/2.8**	**1.6/2.2**	**1.1/2.7**	**1.6/2.3**	**1.9/2.8**	**1.0/2.1**
Resonant Tunneling Devices	**2.6/2.0**	**2.1/2.2**	**2.0/1.4**	**2.3/2.2**	**2.2/2.4**	**2.4/2.1**	**1.4/1.4**	**2.0/2.0**
Molecular Devices	**1.7/1.3**	**1.8/1.4**	**1.6/1.4**	**2.0/1.6**	**2.3/2.4**	**2.6/1.3**	**2.0/1.4**	**2.6/1.3**
Spin Transistor	**2.2/1.7**	**1.7/1.6**	**1.7/1.7**	**1.9/1.4**	**1.6/2.0**	**2.3/2.1**	**1.4/1.7**	**2.0/1.4**
SETs	**1.1/1.2**	**1.7/1.2**	**1.3/1.1**	**2.1/1.4**	**1.2/1.8**	**2.6/2.0**	**1.0/1.0**	**2.1/1.7**
QCA Devices	**1.4/1.3**	**1.2/1.1**	**1.7/1.8**	**1.4/1.6**	**1.2/1.4**	**2.4/1.7**	**1.6/1.1**	**2.0/1.4**

None of the alternative logic technologies in the research community can beat CMOS

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What Are We Looking For?

- Required characteristics:
  - Energy efficiency
  - Performance
  - Scalability
  - Gain
  - Operational reliability
  - Room temp. operation
- Preferred approach:
  - CMOS process compatibility
  - CMOS architectural compatibility

- Potential solutions

  Alternative state variables

  fs, nm functional units

  Assisted self assembly

  Inverted energy populations

  Crystallographic structures

  Non equilibrium systems

- Motivation

  Utilization of existing HVM infrastructure

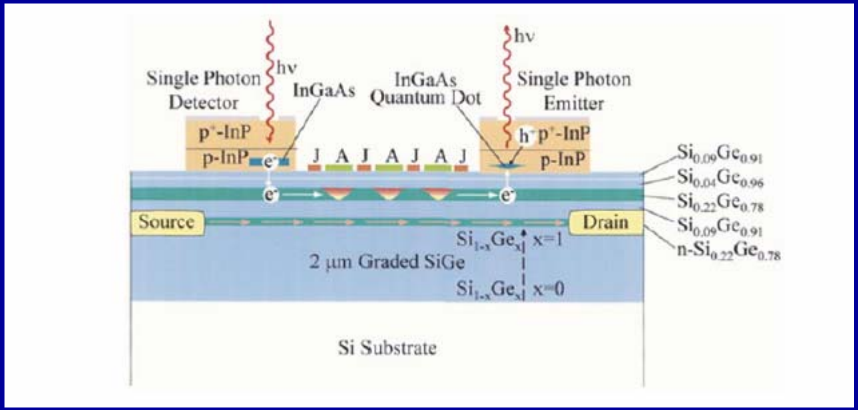
  Utilization of existing software and CAD tools

Energy efficiency <10^{-18} J/op

- Potential solutions
  Alternative state variables
  fs, nm functional units
  Assisted self assembly
  ??
  Crystallographic structures
  Phonon bandgap structures
- Motivation
  Utilization of existing HVM infrastructure
  Utilization of existing software and CAD tools

- Spin–electron, nuclear, photon
- Phase
- Quantum state
- Magnetic flux quanta
- Mechanical position
- Dipole orientation
- Molecular state
- Orbital symmetry
- Order/disorder

Alternative state variables



Quantum Optical repeater- Yablonovitch

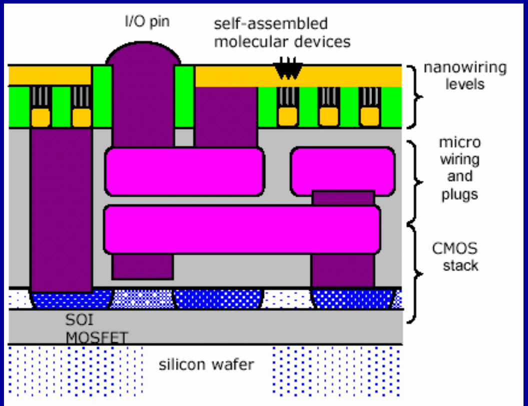
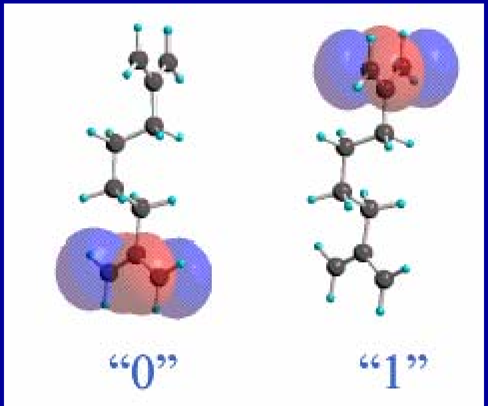


Figure. 1. The general concept of "CMOL" (hybrid CMOS/nanowire/molecular) circuit [4].

Integrated Molecular/ electronics
K Likarhev



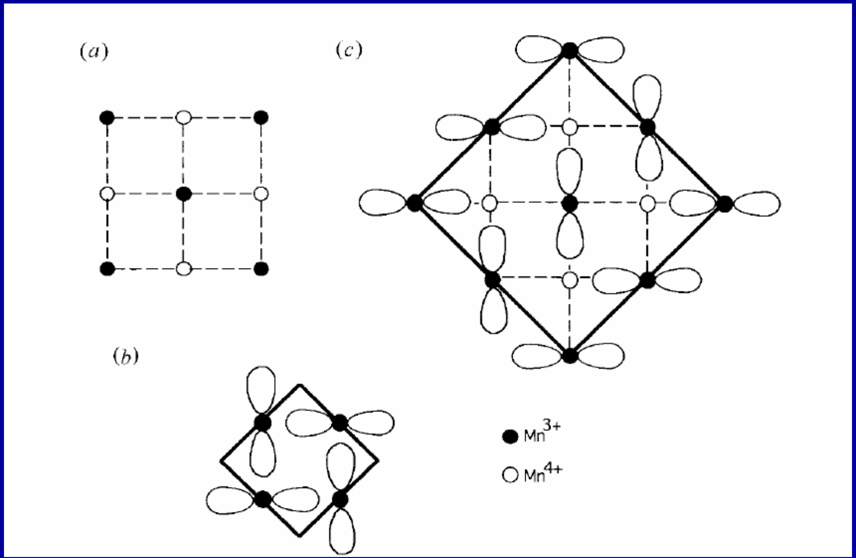
Molecular state – C Lent

Performance <10^{-15}sec, N>10^{12}

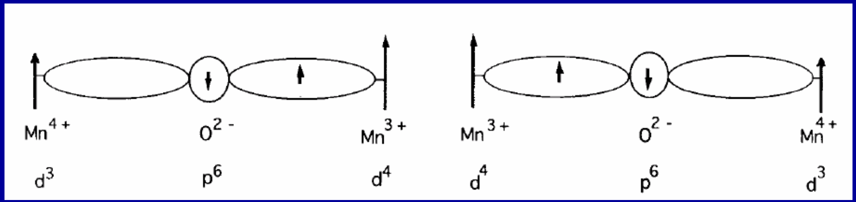
- Potential solutions
  - Alternative state variables
  - **Femptosecond, nano meter functional units**
  - Assisted self assembly
  - ??
  - Crystallographic structures
  - Phonon bandgap structures
- Motivation
  - Utilization of existing HVM infrastructure
  - Utilization of existing software and CAD tools

- Atomic scale functional units
- Parallel data paths, data sets and functional units
- Functional interactions mediated by quantum exchange, double exchange, …interactions
- Nearest neighbor data flows
- Plasmon assisted energy transport

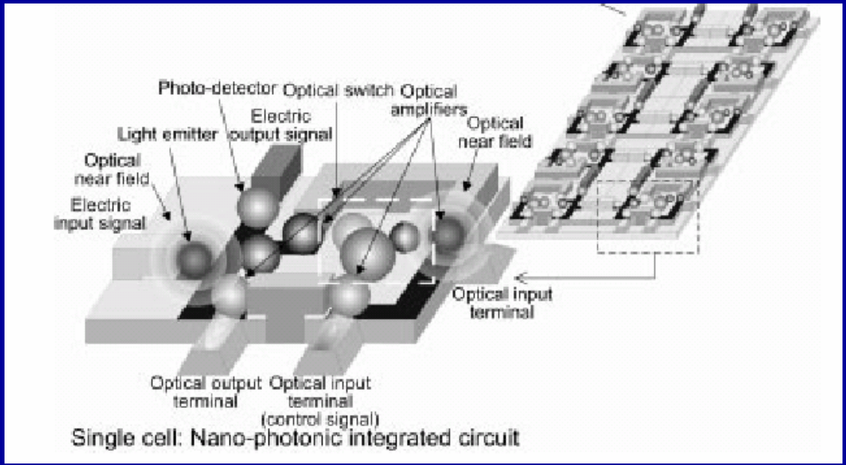
Femptosecond, nanometer scale functional units



Strongly correlated electron systems
M. Coey



Double exchange interaction in MnO_3
M Coey



Near field optical energitics Ohtsu et. al

Scalability

- Potential solutions
  - Alternative state variables
  - fs, nm functional units
  - **Assisted self assembly**
  - ??
  - Crystallographic structures
  - Phonon bandgap structures
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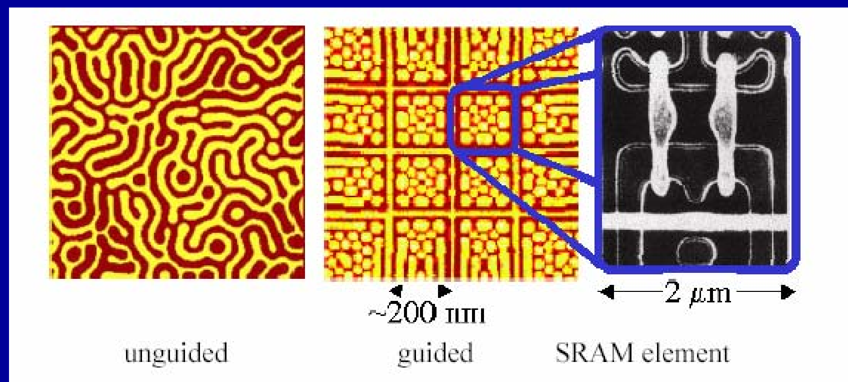
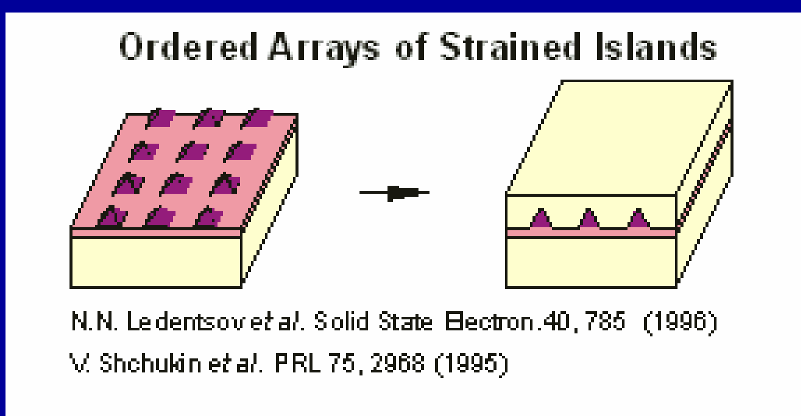
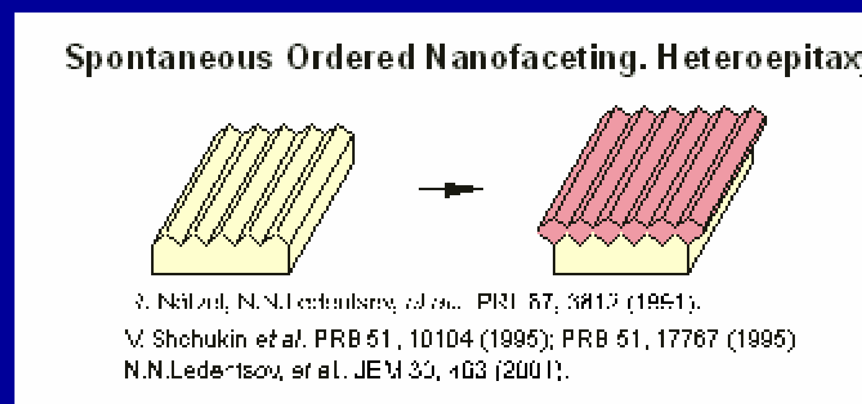
- Lithographically assisted epitaxial strain field modulation
- Lateral templated phase separation

Assisted self assembly



Templated phase separations – Z. Suo, W. Lu J. Nanoparticle Research 2001





Crystallographic strain field nanostructure formation

Room temperature operation

- Potential solutions
  - **Alternative state variables**
  - fs, nm functional units
  - Assisted self assembly
  - Crystallographic structures
  - **Non equilibrium systems**
- Motivation
  - Utilization of existing HVM infrastructure
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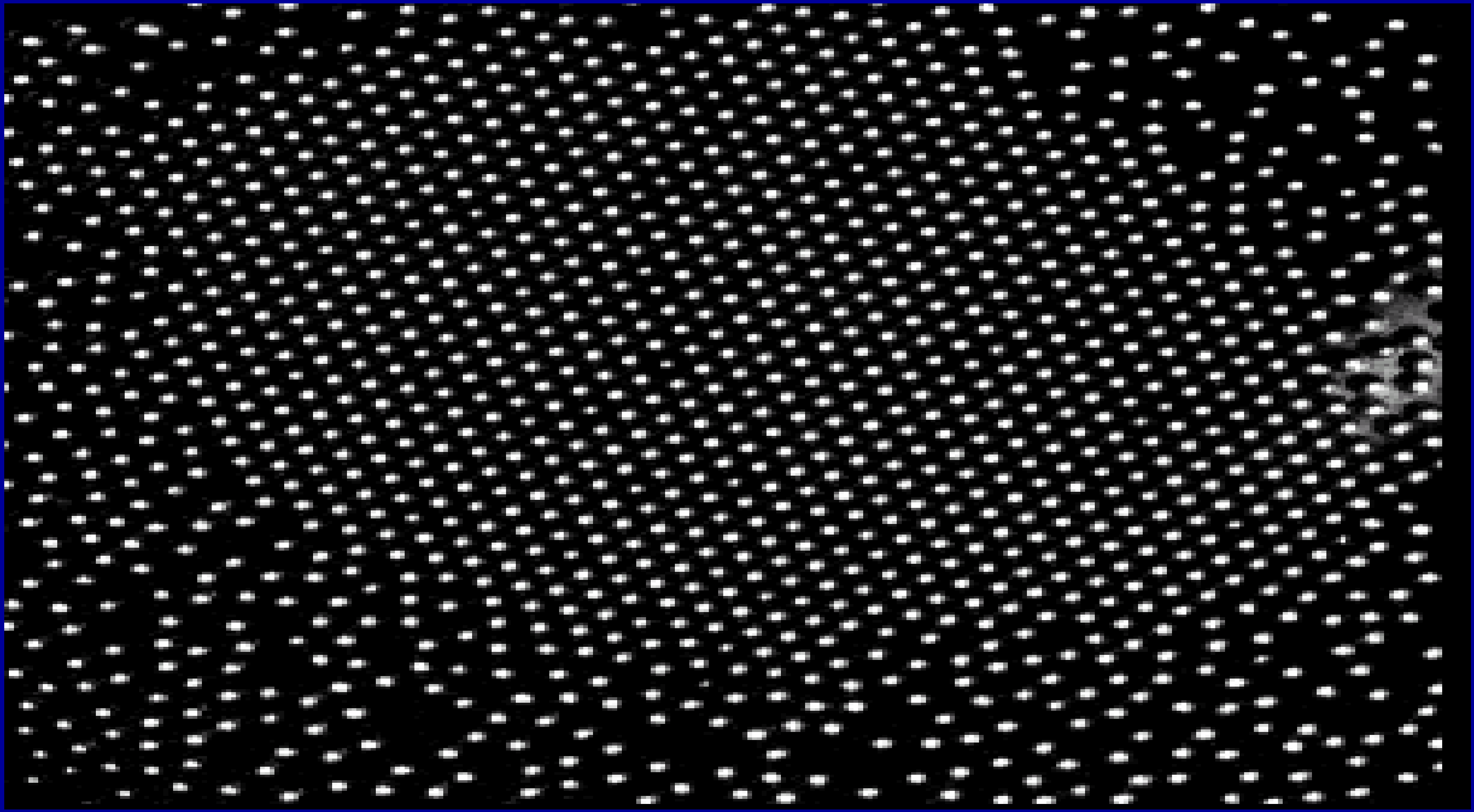
- Engineered Phonon bandgap materials

Non-equilibrium systems

Non-equilibrium ensembles – phonon bandgap engineering



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Putting the pieces together – Functionally organized materials*

Functionally Organized materials

Near field energy transfer

Alternative architectures And data structures

Alternative state variables

Crystallographic Self assembly

Femptosec, nanometer interactions

CMOS process compatibility

Plasmonics

Non equilibrium systems

*ITRS Emerging Research Device Workshop, Stresa Italy, 2004

Definitions

- Functionally organized materials*
  - Material systems which enable distributed and interacting device functionalities in order to store and manipulate computational state arrays
- Metacrystals
  - 3D super lattices of interacting quantum dots, nanocrystals, phonons and plasmons

*Emerging Research Materials Working Group – ITRS 2004

Conclusions

- CMOS will be the logic technology of choice for the indefinite future(15-20 yrs)
- Research to develop robust, new information processing technologies is needed now.
- Relevant scientific pieces exist – *it's time to start putting the pieces together*

For further information on Intel's silicon technology,

please visit the Silicon Showcase at

www.intel.com/research/silicon

Non-equilibrium systems

- The equilibrium postulate - An isolated system in equilibrium is equally likely to be in any of its accessible states
- Non equilibrium systems –
  - Any statistical system where the states are not equally populated
- In order to achieve $E_{op} < KT$, distinguishable states must be isolated from phonon bath